

Theoretical derivation of risk-ratios for assessing wind damage in a coastal forest

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Abstract: Based on the discussion of relationships between thinning and wind damage, and published information, a method for estimating risk ratios of wind damage was developed. Estimations of risk-ratio for *Pinus thunbergii* trees and stands were deduced from stem bending theory and coefficients characterizing wind profile, distribution of branches and optical stratification porosity. The results showed that if the value of constant β in the branch distribution-model equals the attenuation coefficient α_s in the wind profile model for a single tree crown, then the parameter $H/D_{1.3}^3$ (height over stem diameter cubed) can be used to compare and evaluate the risk-ratio of wind damage for individual trees. The same method can be applied to stands using the coefficient of wind profile in a stand, i.e. attenuation coefficient α , the coefficient from distributions of optical stratification porosity, i.e. extinction coefficient ν , and the parameter $D_{1.3}^3$. The application of parameter $H/D_{1.3}^3$ and the process of determining risk ratios of wind damage for stands were also given in the paper.

Keywords: Wind damage; Thinning; Pine forest; Risk-ratio

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Introduction

Wind damage is one of the major constraints on the practice of silviculture (Blackburn and Petty 1988a; Mayer 1989; Rollinson 1989; Quine 1995; Peltola *et al.* 2000). How wind interacts with forests concerns the forest manager in a number of important ways. The influence of wind on forest management and planning can be considered at two main stages in the life of the forest: during and after regeneration (Godwin 1968). Obviously, the influence of wind on the latter, i.e., established stands, has been paid great emphasis, and many studies have been reported (Hutte 1968; Stumbles 1968; Petty and Worrell 1981; Cremer *et al.* 1982; Petty and Swain 1985; Galinski 1989; Peltola and Kellamaki 1993; Quine 1995; Gardiner *et al.* 1997; Peltola *et al.* 1999; Moore and Quine 2000). Almost all of the studies are concerned with timber-production forests. Forest managers, however, need to understand effects of wind in forests used for non-timber purposes. Coastal forests, for example, alter the wind thereby providing protection as well as many other benefits such as recreation, nature conservation, timber, fungi, and berries. Therefore, it is desirable and necessary to make coastal forests resistant to severe damages, especially those re-

sulting from strong wind. However, research in this regard is poorly developed because it has been thought that there is no countermeasure against meteorological extremes that are beyond human control (Matsuzaki 1994). Thinning is one of the few countermeasures against wind damage that can be considered in the management of a forest. However, outcomes of thinning in coastal forest are difficult to determine because, on one hand, thinning can improve the stability of the plantation forest, while on the other hand risk of wind damage increases immediately after any thinning (Cremer *et al.* 1982; Gardiner *et al.* 1997), especially in the coastal area where forests suffer from exposure to relentless winds blowing off the sea (Perry 1994; Zhu *et al.* 2000b).

Although thinning may result in high probability of wind damage, it is necessary to have narrow initial spacing for the survival and growth of the trees in the ruthless coastal area. Therefore, it is important to understand the relationships between thinning and wind damage in detail, and recognize how to estimate the risk of wind damage for a coastal forest stand with various thinning intensities, and what damage will be caused by extreme winds. Managers need basic information on the influences of wind to solve the problems of establishment and management for the coastal forests. Such information could also be useful for researchers of micro and meso-scale meteorology, town and regional planners, and farmers. An understanding of the effects of wind on forests may also be useful for assessing forest health and stability.

We recently completed a study of the influence of thinning on the incidence of wind damage in a coastal pine (*Pinus thunbergii* Parl.) plantation. The objective of the study is to identify (1) how wind damage is related to thin-

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ning, (2) what factors influence the stability of individual trees and stands, (3) what degrees of risk might be quantified after thinning, and (4) how thinning strategy should be designed to reduce risks of wind damage for the management of coastal pine forests. Here we present a review of relationships between wind damage and stand density or thinning in timber-production forests, and develop a method of wind damage-risk estimation for individual trees and stands on the basis of published information (Blackburn and Petty 1988b; Galinski 1989).

Thinning and the risk of wind damage

Wind damage can be mainly classified into stem damage and canopy damage. The most common report is stem damage, which includes uprooting, breakage, and bending or leaning (Everham 1995). Canopy damage may be quantified directly on the basis of branch loss, canopy damage or defoliation.

Generally, thinning entails risk of wind damage, i.e., the likelihood of damage due to strong winds, in the short term (Cremer *et al.* 1982; Quine 1995). Particularly, it could have an important and unanticipated impact on the occurrence of wind damage where the climate is windy and sites are poor (Quine 1995). It has been reported that the stabilities of trees and stands are reduced after thinning, and the degree of the destabilization, i.e., the risk of wind damage caused by thinning, depends not only on meteorological factors but also on site conditions (topography, soil type, soil water content etc.), forest structure (forest age, height, density etc.) and the pattern and intensity of thinning (Cremer *et al.* 1982). The relationships between thinning and the risk of wind damage can be summarized from levels of both single tree and stand as follows.

1) The removal of neighboring trees results in an opening of the canopy, and the wind gusts penetrate deeper.

2) The wind protection from the neighboring trees and the mechanical crown contact are reduced by thinning. The two kinds of reductions contribute to increased tree sway amplitudes, i.e., the increase of destructive storm moment (Gardiner 1995; Nielsen 1995).

3) It is the thinning that increases the aerodynamic roughness of the canopy surface and turbulence. This will enhance the momentum transfer from wind to stand. The increased amount of transferred energy is distributed to a reduced number of trees per hectare, i.e., the overall wind load has to be shared by the reduced number of remaining trees. Thus, thinning increases the destructive storm moment of the retained trees (Cremer *et al.* 1982; Nielsen 1995; Peltola 1996a).

It has been suggested that the most dangerous situation arises when the wind spectrum includes strong gusts whose frequency coincides with the natural frequency of oscillation of the trees (Peltola *et al.* 1993; Gardiner 1995). It may indeed be totally inadvisable for thinning in stands which are already weak because of overstocking, and

perhaps also in stands where root development is extremely restricted (Cremer *et al.* 1982; Ruel *et al.* 1998).

Conversely, thinning reduces the risk of wind damage by improving the stand stability in the long term. With the growing of trees, the thinned stand will gradually regain the stability and become stronger than before the thinning (Matsuzaki 1994). The increased diameter growth achieved at lower stocking or density is generally higher than height growth (Deans and Milne 1999). This attributes not only to the fact that each tree gains better access to light (Cremer *et al.* 1982), water and nutrients (Kuraji *et al.* 1997), but also to the fact that the increased exposure to wind results in more swaying (Cremer *et al.* 1982; Telewsiki 1995). A study of thigmo-morphogenesis (Telewsiki and Jaffe 1981) indicated that swaying increased diameter growth and decreased height growth. Thus, thinning can reduce the ratio of $H/D_{1.3}$ or increase taper ($D_{1.3}/H$) of trees (H is tree height, $D_{1.3}$ is diameter at breast height, 1.3 m). Exposure to wind also tends to increase growth of roots (Grace 1988; Stokes *et al.* 1995), and thus improves the tree strength and stability. Long after thinning, stands redevelop a smooth canopy surface, low momentum transfer to the canopy, high wind protection between the neighboring trees, and high reduction of tree sway amplitudes and increment of strength.

The time needed to regain certain stability for thinned stands depends on the growth rate, stand age and the state of the stand at the time of thinning. Generally, the changes of thinning are the most significant when the duration of their effect (time for crowns to grow back) is not longer than recurrence interval of the appropriate threshold wind speed (Quine *et al.* 1999).

In a word, thinning is one of the most important countermeasures for the sustainable forestry to prevent wind damage (Matsuzaki and Nakata 1993); however, the forest soon after thinning is vulnerable to strong wind because it does not quickly recover resistance to extreme wind. Resolving the dilemma between the benefits and risks of thinning may require management skill, and luck.

Index for the risk of wind damage

The risk of wind damage is subject to very complex factors associated with the stature of trees, the aerodynamic properties of a stand, the general and local incidence of winds, soil conditions, and so on. These factors can be classified as three main aspects, i.e., weather, site and stand conditions (Cremer *et al.* 1982). The weather conditions are always beyond human control (Matsuzaki 1994), the site conditions are mainly permanent for a special location, while the stand conditions are the most important and controllable, and the features of a stand are subject to change with growth and silvicultural measures. Therefore, the important effects of stand structure or configuration on wind loading have been dealt within many studies (Cremer *et al.* 1982; Petty and Swain 1985; Galinski 1989; Gardiner

et al. 1997).

Foresters have used the ratio of $H/D_{1.3}$ or taper $D_{1.3}/H$ as a measure of risks of wind and snow damage (Valinger and Pettersson 1996). The ratios of $H/D_{1.3}$ were calculated in several ways, but mostly from the mean height and diameter of all the trees in the stand. However, Cremer *et al.* (1982) suggest that both tree height (H) and diameter ($D_{1.3}$) calculated from the mean values of the 200 largest stems per hectare, i.e., H_{200L}/D_{200L} (where H_{200L} and D_{200L} are the mean tree height and mean $D_{1.3}$ of the largest 200 stems per hectare) can be considered as a valuable index of the risk of wind damage. This is because that smaller trees are far less significant than the dominant trees in determining the stability of the stand, and selective removal of the smaller trees by thinning will at once boost the ratio of $D_{1.3}/H$, and thus may wrongly suggest that the risk is lowered. Ratio of $H/D_{1.3}$ is considered as the most important factor likely to influence the stability of stand (Petty and Worrell 1981; Cremer *et al.* 1982; Blackburn and Petty 1988b).

Other ratios of height and diameter have been used as alternatives to $H/D_{1.3}$, for example, $H/D_{1.3}^3$, $H/D_{1.3}^2$ and $H^{3/2}/D_{1.3}$. Generally, $H/D_{1.3}^3$ relates to the strength of a cantilever of uniform resistance (Gardiner *et al.* 1997). $H/D_{1.3}^2$ is closely related to the shape of tree stem (Cremer *et al.* 1982). And $H^{3/2}/D_{1.3}$ gives the greatest relative weight to tree height and relates best to elastic strength properties (Valinger *et al.* 1993).

The relationships between the index values and incidence of wind damage showed that the combination of height and diameter in $H/D_{1.3}$ was valuable for providing the first indication. However, risk of wind damage depends not only on the sturdiness of the tree population but also on the aerodynamic properties of the stand, as well as on wind conditions, therefore, the relationships between the above mentioned index values and incidence of wind damage can only provide a broad indication of risk.

Estimation of risk of wind damage

Foresters need a practical measure to assess the risk of wind damage for a particular tree or stand. Blackburn and Petty (1988b) and Galinski (1989) suggest a practical method for evaluating the risk of wind damage from the combination of stem bending theory and wind regime. The fundamentals of this method are accepted in this paper also, but some details are developed for estimating the risk of wind damage for a single tree (*Pinus thunbergii* Parl.) and for a coastal stand of the same tree species.

Estimation of risk-ratio for individual tree

The diagnosis of wind risk for individual trees and stands requires evaluation of how well trees or stands are acclimated to wind load (Mitchell 2000). Firstly, it is assumed that a single tree of *P. thunbergii* can be modeled as an elastic beam with constant modulus of elasticity. Wind act-

ing on the tree crown creates a drag force, which when acting along the stem produces increasing turning moments towards the base of the tree (Galinski 1989). These moments are resisted by the strength of stem and the root-soil system, and the drag force that causes the tree to be bent results from wind action (Galinski 1989; Mitchell 2000). If it is assumed that the main cause of the drag force is the presence of needled tree branches which can be approximately characterized by their length (Galinski 1989), then the momentum exchange between moving air (wind) and the tree branches causes the drag force which for a given tree is nearly proportional to the wind speed (Peltola 1996b). Therefore, the drag force in a single whorl or verticil of branches in a single tree can be represented by equation (1) (Galinski 1989).

$$F_i = kL_i U_z \quad (1)$$

where k is constant coefficient, F_i is the drag force (N), L_i is the total length of needled branches in i th whorl from the base, U_z is wind speed within a single crown corresponding to the height of the i th whorl ($m \cdot s^{-1}$).

The length of needled branches is summed over the whorl because the influence of the wind direction is not considered. Galinski (1989) suggests the principle of equation (1) for conifer trees is as follows: the whorl is the smallest reasonable unit for which the drag force can be calculated without considering the behavior of each branch under wind action. The leeward branches are bent into a parallel position to the wind speed vector, and the windward branches are strongly deflected from the position by wind. Thus, it is reasonable to assume that the whole whorl resistance results from wind speed and the sum of needled branches in the whorl.

Wind speed within a single tree crown of *P. thunbergii* obeys the exponential form given in following equation (Zhu *et al.* 2000a).

$$U_{sz} = U_{out} \exp[-\alpha_s(1 - H_i/H)] \quad (2)$$

where H_i is the height of interest within the canopy (m), H is maximum height of the tree crown (m), U_{sz} is wind speed ($m \cdot s^{-1}$) inside the canopy at height z , U_{out} is wind speed ($m \cdot s^{-1}$) outside the canopy at a certain height (generally at 2 m, i.e. $U_{out} = U_{z=2m}$), it can also be replaced by U_H (wind speed at the tree top, $m \cdot s^{-1}$) because $U_H/U_{out} = (1/\kappa) \ln[(z-d)/Z_0]$ (logarithm law, U_{out} is friction velocity, $m \cdot s^{-1}$, κ is the von Karman constant, d is zero-plane displacement, m, Z_0 is roughness parameter, m), and α_s is a constant, which determines the form of wind profile within the single tree crown.

Replacing U_{sz} in equation (1) with equation (2) results in:

$$F_i = kL_i U_{out} \exp[-\alpha_s(1 - H_i/H)] \quad (3)$$

The bending moment in basal cross-section (M) resulting from action of the drag force F_i equals:

$$M_i = H_i F_i = k H_i L_i U_{out} \exp[-\alpha_s (1 - H_i / H)] \quad (4)$$

and the total bending moment (M_{ts}) equals the sum over all whorls along the whole tree height.

$$M_{ts} = \sum H_i F_i = k U_{out} \sum H_i L_i \exp[-\alpha_s (1 - H_i / H)] \quad (5)$$

However, the parameter of L_i is unique for each tree species, for *P. thunbergii*, the distribution of L_i increases exponentially with decreasing height (Zhu *et al.* 2000a), i.e.,

$$L_i = \exp[\beta(1 - H_i / H)] \quad (6)$$

where β is constant coefficient.

Replacing L_i in equation (5) with equation (6), equation (5) becomes:

$$M_{ts} = k U_{out} \sum H_i \exp[\beta(1 - H_i / H)] \exp[-\alpha_s (1 - H_i / H)] = k U_{out} \sum H_i \exp[(\beta - \alpha_s)(1 - H_i / H)] \quad (7)$$

According to the proposition by Galinski (1989), if every transverse cross-section of the stem is circular, the strain in its outer wood is given by equation (8) (Galinski 1989; Blackburn and Petty 1988a, b).

$$S(t) = 4 M_{ts} / D_{1.3}^3 \pi \quad (8)$$

where $S(t)$ is strain in stem outer wood (N), π is Pythagoras constant, 3.1416.

Integrating equations (7) and (8) results in:

$$S(t) = \{4 k U_{out} \sum H_i \exp[(\beta - \alpha_s)(1 - H_i / H)]\} / D_{1.3}^3 \pi \quad (9)$$

For a given wind speed U_{out} , the differences in tree architecture cause a difference in risk of wind damage for

particular trees. Thus, it is possible to define the risk of wind damage as the individual tree architecture contribution to the strain from equation (9).

As $4 k U_{out} / \pi$ is constant for a given wind speed outside the tree crown, the risk-ratio $R(s)$ suggested by Galinski (1989) can be defined as,

$$R(s) = \{ \sum H_i \exp[(\beta - \alpha_s)(1 - H_i / H)] \} / D_{1.3}^3 \quad (10)$$

Galinski (1989) suggests that the variation of individual ratio, $R(s)$ is relatively low for most trees. This suggests that a unique value of $R(s)$ exists for each tree and it is independent of the site. Therefore, equation (10) can be used to evaluate or compare the risk of wind damage for individual trees.

For tree species of *P. thunbergii*, we found that if U_{out} in the model of wind speed within the single-tree crown (equation 2) is replaced by U_H , then the value of coefficient α_s in equation (2) nearly equals coefficient β in equation (6). In order to simplify the expression of the problem (equation 10), we can assume that coefficient β equals α_s in value, which means that equation (10) becomes:

$$R(s) = H / D_{1.3}^3 \quad (11)$$

The simple expression of risk estimation of $R(s)$ (equation 11) allows a comparison of growth strategies among individual pine trees. The higher the $R(s)$ is, the higher the probability that the considered tree will be destroyed during a strong wind.

The risk estimation of $R(s)$ for the *P. thunbergii* trees in a coastal forest, which was thinned in four treatments, i.e., 0, 20%, 30% and 50% thinned, which are referred to treatment 1, treatment 2, treatment 3, and treatment 4, respectively, was conducted. Figures 1A and 1B are the distribution of stems by risk ratios of individual trees soon after the thinning (December of 1997) and two years after thinning (January of 2000).

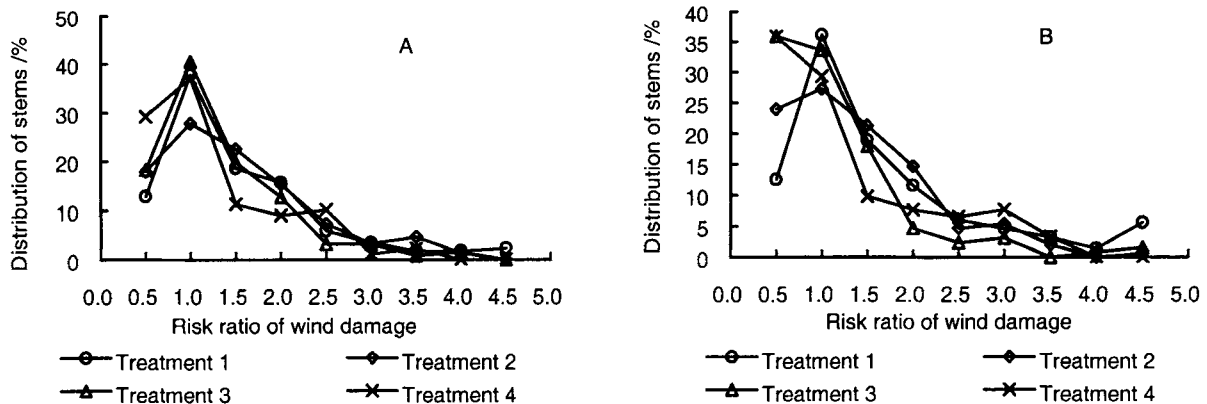


Fig. 1 The distribution of stems sorted according to risk ratios

A: soon after the thinning, and B: two years after thinning

The proportion of stems with higher risk-ratios of wind damage (H/D_1^3 more than 2.5) plotted in Figures 2A and 2B showed that stems of higher risk-ratios increased in the

unthinned treatment, but decreased in the 20% thinned treatment (the same as in other thinned treatments).

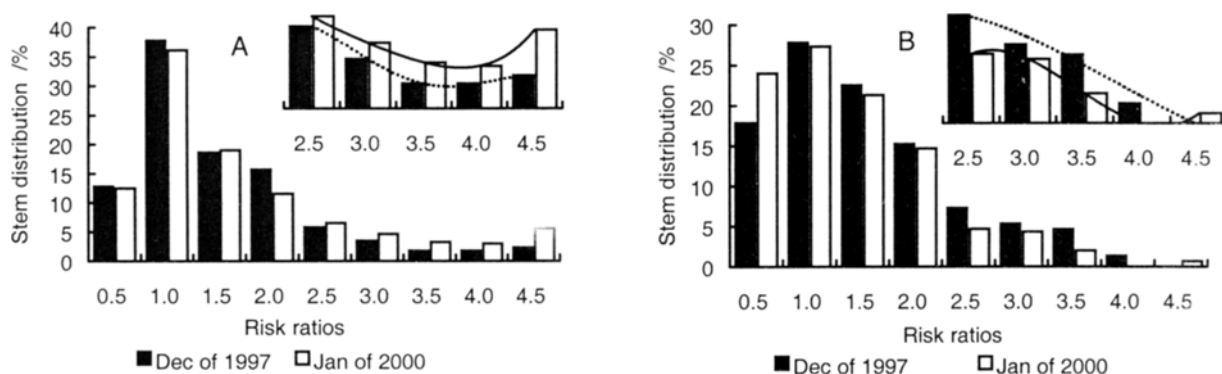


Fig. 2 Changes of the risk ratios

A: unthinned, and B: 20% thinned

Estimation of risk-ratio for stand

Applying the same approach used for a single tree, we can assess the risk of wind damage for a forest stand as follows.

If the dynamic wind load is the presence of area of the canopy and stem, the momentum exchange between moving air (wind) and the tree elements in the stand, which causes the drag force, can be estimated from the wind speed profiles within the canopy (Peltola *et al.* 1993; Peltola 1996b), i.e.,

$$F_d(z) = kF_s(z) = k(0.5C_d \rho A_z U_{tz}^2) \quad (12)$$

where $F_d(z)$ is the drag force or dynamic wind load (N), $F_s(z)$ is the static wind load (N), C_d is the drag coefficient (dimensionless), here assumed to be constant, ρ is the air density ($\text{kg}\cdot\text{m}^{-3}$), A_z is the projected area of the crown and stem (m^2) at height z , and can be approximated as equation (13), U_{tz} is wind speed ($\text{m}\cdot\text{s}^{-1}$) at height z within the canopy.

$$A_z = B_z dz \quad (13)$$

where B_z represents the leaf area index (dimensionless).

As parameters k , C_d and ρ are constant, let

$$k(0.5C_d \rho) = \xi \quad (14)$$

Then equation (12) becomes,

$$F_d(z) = \xi U_{tz}^2 B_z dz \quad (15)$$

Using the same principle as for the single-tree, the total bending moment for a stand, M_H equals:

$$M_H = \int_0^H z F_d(z) dz = \xi \int_0^H z B_z U_{tz}^2 dz \quad (16)$$

Wind speed within the canopy obeys the exponential form given in equation (17) (Bergen 1971; Landsberg and James 1971; Amiro 1990; Wenzal *et al.* 1997; Zhu *et al.* 2001a, b).

$$U_{tz} = U_H \exp[-\alpha(1 - z/H)] \quad (17)$$

where z is the interest height within the canopy (m), H is height of top of tree canopy (m), U_H is wind speed ($\text{m}\cdot\text{s}^{-1}$) at height H , coefficient α is called as attenuation coefficient.

B_z can be represented by the distribution of optical stratification porosity (OSP) (Zhu *et al.* 2000b, 2002).

$$B_z = d\{\exp[-\nu(1 - z/H)]/dz = (\nu/H) \exp[-\nu(1 - z/H)] \quad (18)$$

where ν is extinction coefficient of distribution of OSP (Zhu *et al.* 2000b, 2002).

Combining equations (16) and (18) results in:

$$\begin{aligned} M_H &= (\xi U_H^2 \nu / H) \int_{H_0}^H z \exp[-\nu(1 - z/H)] \{\exp[-\alpha(1 - z/H)]\}^2 dz \\ &= (\xi U_H^2 \nu / H) \int_{H_0}^H z \exp[-(\nu + 2\alpha)(1 - z/H)] dz \end{aligned} \quad (19)$$

where H_0 is bole height (m).

For a given stand, the strain, $S(ts)$ in equation (8) for stands, is given by the same form as that of the single tree.

$$S(ts) = (\xi U_H^2 v / H) \int_{H_0}^H z \exp[-(v + 2\alpha)(1 - z/H)] dz / D_{1.3}^3 \pi \quad (20)$$

As $\xi U_H^2 v / H$ is constant for a given wind speed at the canopy top, the risk-ratio $R(t)$ for a stand can also be expressed as

$$R(t) = \int_{H_0}^H z \exp[-(v + 2\alpha)(1 - z/H)] dz / D_{1.3}^3 \quad (21)$$

$D_{1.3}$ in equation (21) is the mean diameter of the stand calculated from various sample patterns (mean $D_{1.3}$ of all stems, mean $D_{1.3}$ calculated from the mean values of the 200 largest stems per hectare and so on). Risk estimation of $R(t)$ allows a comparison of growth strategies among different stands. The higher the $R(t)$ is, the higher the probability that the considered stand will be destroyed by the strong wind, i.e., $R(t)$ can be used to measure and compare the risk of the growth strategy and the thinning measures adopted by the stand. The following scheme (Fig. 3) presented the process of determination for $R(t)$.

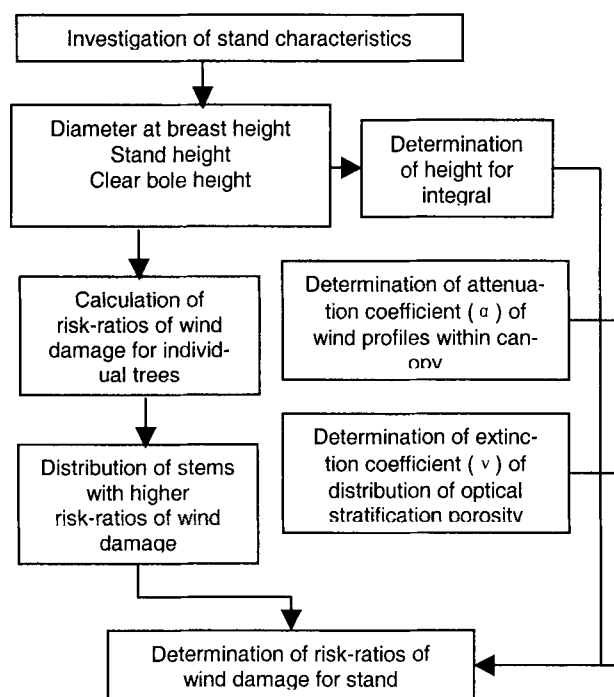


Fig. 3 Scheme for determining risk-ratios of wind damage

Summary

The methods for determining risk-ratios of wind damage for both individual trees and for stands were developed by theoretical derivation on the basis of bending theory. It was found that $H/D_{1.3}^3$ values could be used to evaluate the risk of wind damage for individual trees. The attenuation coefficient of a wind profile and the extinction coefficient of the

distribution of optical stratification porosity, combined with $D_{1.3}^3$ could be used to compare the risk of wind damage among forest stands. The basic application of the methods is to determine the relative risk of wind damage for individual trees and stands; in addition, it can be used to compare the risk of the growth strategy and the thinning measures adopted by the stand. Although the results discussed above may not be directly applicable to other type of forests and other tree species, the risk-ratios of wind damage can also be obtained according to special tree species using the procedures discussed in this paper.

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